Ecological condition of US National Parks: Enhancing decision support through monitoring, analysis, and forecasting.

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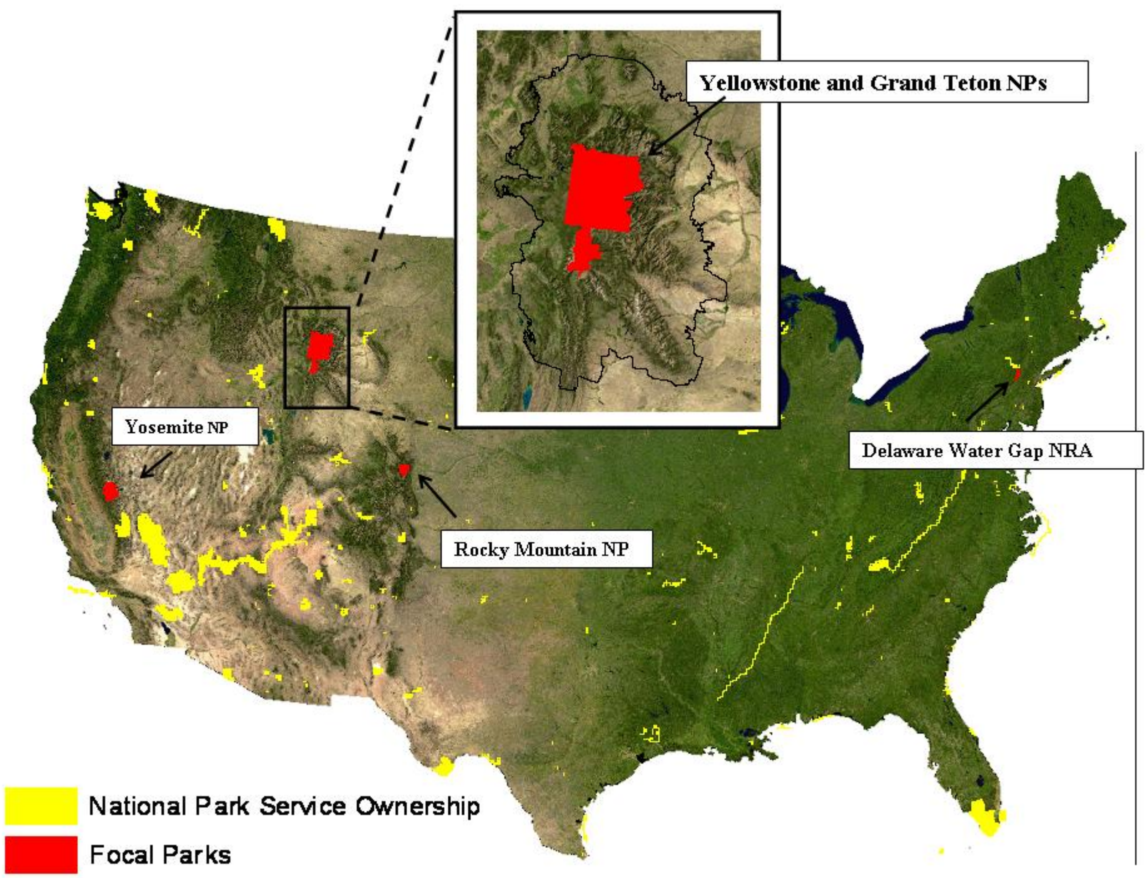
Proposal to NASA Decision Support Through Earth-Sun Science Research Results
Spring 2006



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Decision Support Overview/Baseline

A fundamentally important component of the nation's effort to maintain a high quality environment is management of lands to sustain ecological processes and to protect biological diversity (Leaderwilliams et al. 1990, Halvorson and Davis 1996, Arcese and Sinclair 1997, Shafer 1999, Dale et al. 2000). Public and privately-owned protected areas include national parks, wildlife refuges, nature reserves, and other lands. Historically, it was widely believed that the ecological structure and function of these areas could be protected by simply prohibiting incompatible human uses. A more contemporary view recognizes that the internal dynamics of protected areas respond in sensitive ways to their surrounding context (GAO 1994, Pickett et al. 1992, Hansen and Rotella 2002, DeFries et al. 2005). Examples of the influence of context include cross boundary movements of mobile native fauna, intrusions of materials in air and water, modification of fire regimes, and invasion by exotic species. Moreover, patterns of natural succession and responses to episodic disturbance create spatially dynamic landscapes within protected areas, and these dynamics have fundamental implications for policy and management. Thus, a central challenge in efforts to assure environment quality in the United States depends on assessing and managing dynamic landscapes within protected areas and their surroundings (Slocombe 1992, Halvorson and Davis 1996).

Through the first 100 years of its existence, the NPS had a poor record for monitoring natural resources in parks, and for using science to guide management decisions (Sellars 1997). While many parks have spatial analysis capabilities, few parks used these capabilities to track changes in ecosystem condition. Consequently, management decisions are often made without key information on trends and conditions of park resources.

To address these deficiencies in monitoring and analysis, Congress authorized the Natural Resource Challenge in 1998, which established the NPS Inventory and Monitoring Program (NPS I&M) as the primary source of scientific information to support decisions on management of natural resources in parks. The NPS I&M was been charged with implementing a system to assess indicators of health for more than 270 National Park units. In response to this mandate, the NPS I&M has developed a decision support system (DSS) consisting of conceptual models, databases, and accompanying analytical tools. The immediate purpose of the DSS is to monitor and anticipate change in the "vital signs" of park ecosystems and their surroundings to improve decisions on policy and management. Each of 32 NPS I&M Program monitoring Networks (groups of parks) adapts the general DSS to best address their local conditions. Initial workshops with I&M Networks identified change in land cover and use as a key vital sign; it was selected as a priority more frequently than any other considered. This result creates a timely opportunity to use NASA Earth-Sun science (ESS) products to assist ongoing efforts to map and monitor landscape dynamics relevant to the health of the nation's parks and protected areas.

Although there is tremendous potential to add value to the NPS I&M DSS with NASA ESS products, there are a number of obstacles to overcome. Monitoring land cover and land use to support decisions on park management raises difficult conceptual issues (Hobbs 2003); for example, delineating the area around parks that should be monitored, identifying aspects of land cover and use that are the highest priorities for management, and determining how to assess the effects of change in land cover and land use on park resources, such as biodiversity (Hansen and Gryskiewicz 2003). There are technical issues as well. Many NASA ESS products require considerable effort to make them useful for NPS I&M applications. Monitoring data are most useful when put in the context of change over time or analyzed in conjunction with other data to reveal effects relevant to management objectives. Data must be converted into suitable formats and used to conduct integrated assessments that consider land cover types, land use and disturbances, impacts to habitat quality, habitat isolation, pollution threats to biota, and other landscape attributes. Finally, results of analyses need to be offered in formats that are accessible and useful to decision-makers.

The goal of this study is to increase the effectiveness of the NPS I&M DSS by the delivery, analysis, and display of NASA ESS data, models, and science results. The approach is to enhance the DSSs created by I&M Networks by standardizing rigorous conceptual models, integrating a system to routinely deliver highly relevant NASA data and products, using these NASA data for monitoring and forecasting changes in land use and land cover in and around parks, and providing integrative software systems for reporting results. The collaboration will be facilitated by a recently signed Memorandum of Understanding between the NPS and NASA that details clearly stated goals of cooperation on the development of protocols for analyzing remotely sensed data and predictive models to support common scientific and educational activities. We will develop and demonstrate the approach in four I&M pilot Networks. I&M staff will be trained to use and maintain the system, and we will work with the NPS I&M national office to integrate the approach into the nationwide DSS.

We have assembled a seasoned, experienced, and balanced team of investigators and collaborators with strong connections to NASA and NPS. Our team has broad experience in using NASA data to represent landscape changes in diverse landscapes (Theobald 2001; Jantz et al. 2003; Parmenter et al. 2003; Wessels et al. 2004), including an interactive web-based DSS developed for the Rocky Mountain Region (Theobald et al. 2000; Theobald and Hobbs 2002; Hernandez et al. 2005) and a national assessment of private-land forest change (Stein et al. 2004). Dr. Hansen is an expert in land use change and effects on biodiversity, especially in the context of greater park ecosystems. NASA has funded his work for Yellowstone (NAG5-11158, NAG5-9300), North America (NNG04GL02G, number pending), and internationally (NAG5-6005). He has applied results of these studies into assessments of two NPS I&M Networks. Dr. Goetz is well known for remote sensing of land cover change and applied use, including in hydrology modeling (NAG513397, NAG1303031). He has used these tools for NPS I&M Networks in the eastern US. Dr. Theobald has pioneered spatial analyses of land use, especially in the context of biodiversity. He has also developed and implemented a highly successful interactive web-based DSS for the Rocky Mountain Region (Theobald et al. 2000; Theobald and Hobbs 2002). Dr. Gross is the national landscape ecologist for the NPS I&M Program. He has been the leading intellectual force in the development of landscape aspects of the I&M DSS. He has very strong ties to I&M Network scientists and is uniquely positioned to ensure a seamless relationship between the research team and the NPS I&M. Dr. Nemani and F. Melton are highly respected global ecosystem modelers with extensive experience in system engineering and software design. Dr. Nemani originated and directs the TOPS program and is the P.I. on a NASA REASoN grant to integrate NASA ESS products into the NPS I&M DSS. Finally, scientists from each of the collaborating I&M Networks will work with us to ensure that the data, products, and DSS are highly relevant and useful to the NPS managers.

Earth-Sun System Research Results

NASA Sensors/platforms:	*MODIS/TERRA; ASTER/TERRA; MODIS/AQUA; Landsat TM; Landsat ETM+; AVHRR; VIIRS/NPP*
NASA Models:	*Terrestrial Observation and Prediction System (TOPS)*

The study will use a range of ecosystem models and analysis techniques to incorporate data products from NASA satellites and ecosystem models generated by the Terrestrial Observation and Prediction System (TOPS) in operation at NASA Ames Research Center (http://ecocast.arc.nasa.gov). The project will leverage TOPS procedures for automated retrieval, processing, and integration of NASA ESS data sets, including those from the AQUA, TERRA, and Landsat platform sensors. At minimum, this project will utilize data from the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument onboard TERRA and AQUA, Advanced Spaceborne Thermal Emission and Reflection Radiometer onboard TERRA, as well as historical Landsat and AVHRR data. TOPS also provides capabilities for rapid integration of data from new sensors as they become available, and this project will evaluate demonstration products provided from new sensors currently available or planned for launch prior to 2008, such as the Visible/Infrared Imager/Radiometer Suite (VIIRS) onboard the planned NPP satellite.

As described in the following sections, we will also make use of multiple data products from NASA ESS models to increase the utilization of data derived from NASA satellites for management of U.S. National Parks. Outputs from TOPS component ecosystem models will be used to develop historical baselines of ecosystem conditions and provide long-term forecasts to assist in park management. We will leverage procedures currently being established with support from NASA to incorporate products derived from TOPS into the NPS I&M DSS. Under this project, we will extend those capabilities to include long-term forecasting and scenario evaluation. Currently, TOPS integrates data from satellite and ground-based observation networks to produce a comprehensive suite of over 30 variables describing land surface and ecosystem conditions. These products include data from satellites (land cover, snow cover, surface temperature, vegetation density, vegetation productivity), surface weather stations (max/min temperatures, humidity, solar radiation and rainfall) and modeled fluxes (soil moisture, vegetation stress). Historical climate data and long-lead climate forecasts will also be used to drive TOPS models to develop forecasts of ecosystem conditions for use in the I&M DSS.

TOPS data products to be incorporated into the NPS I&M DSS:

MODIS (from TOPS)
- LAI (Leaf Area Index)
- FPAR (Fraction of absorbed Photosyn. Active Radiation)
- LST (Land Surface Temperature)
- NDVI (Normalized Difference Veg. Index)
- Land cover (Annual)
- Snow

Meteorology
- Maximum Temperature
- Minimum Temperature
- Rainfall
- Solar Radiation
- VPD (Vapor Pressure Deficit)

TOPS Ecosystem Products
- Snow
- Outflow
- Soil Moisture
- Phenology

TOPS-BGC Forecasts
- LAI
- Soil Moisture
- ET (Evapotranspiration)
- Phenology
- Snow

Technical/Scientific/Management Section

Rationale and Objectives

The need for monitoring and decision support for US National Parks is heightened by the rapid change that is occurring in and around parks. These changes include key drivers of ecosystem function such as climate and hydrology and changes in human society leading to redistribution of populations and increased park recreation. Climate has warmed in many locations in the US over the last century and variability in temperature and precipitation has increased (Groisman et al. 2004). In some National Parks, these changes in climate have led to increased fire, more frequent low stream flows, and reduced net primary productivity (NPP) (Brown et al. 2004, McKenzie et al. 2004, Hicke et al. 2002). Similarly, many National Parks have experienced rapid changes in land use on the surrounding lands. Increases in agriculture, rural homes, and cities have reduced the area of natural habitats around parks and resulted in losses of biodiversity (Parks and Harcourt 2002; Theobald 2003; Jantz et al. 2005). To effectively manage National Parks, NPS personnel must be able to regularly track changes in key resources and factor these changes into decision making.

The goal of our study is to integrate the routine acquisition and analysis of NASA ESS products and other data sources into the NPS I&M DSS and use these NASA products to evaluate and forecast ecological condition of US National Parks, thereby enhancing natural resource management within and surrounding national parks. Our objectives are as follows.

1. Select landscape-level indicators of NPS "vital signs" consistent with the conceptual models imbedded in the NPS I&M DSS and identify the boundaries of the greater park ecosystem appropriate for these indicators.
2. Establish procedures to directly incorporate existing spatial data and products from the NASA-sponsored Terrestrial Observation and Prediction System (TOPS) and other sources.
3. Add value to these spatial data sets for NPS management by using ecological knowledge to guide the analysis and portrayal of changes in land use/cover, climate, ecosystem productivity, hydrology, and biodiversity and the indicators developed in #1, and to forecast likely ecosystem changes given alternative decision scenarios.
4. Integrate the data acquisition, analysis, forecasting, and display of these ecosystem changes into the NPS I&M's decision support framework.

Overview of Study Design

The study is designed within the NASA Applications Program framework (Fig. 1). Earth observations and NASA ESS models are used as inputs to generate observations and predictions that enhance the NPS I&M DSS and inform NPS management decisions and policy. The Earth Observation Inputs include NASA ESS data relating to climate, hydrology, ecosystem productivity, and land cover. They also include socioeconomic and land use data from other sources. The family of models within the TOPS framework is used to make hindcasts and nowcasts of ecosystem condition and forecasts of likely conditions under alternative management strategies. These predictions and the raw observations from monitoring are incorporated in the NPS

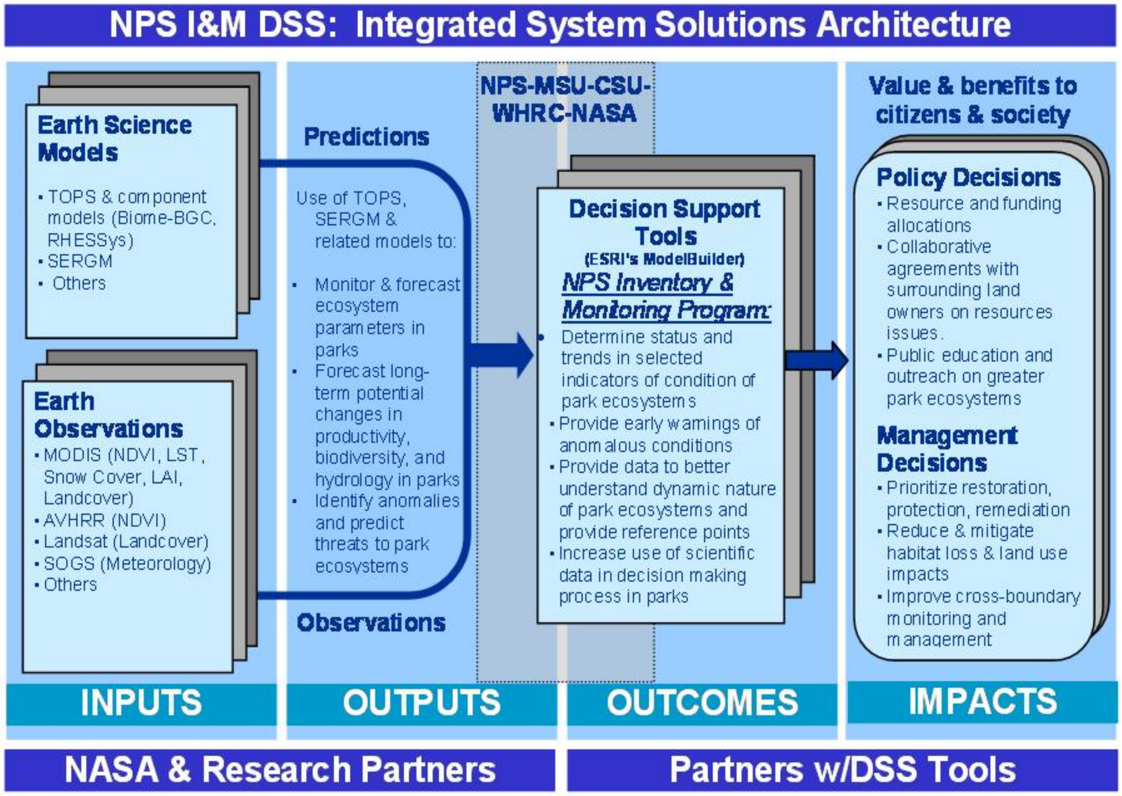

Figure 1. Integrated System Solutions architecture for the proposed project. The National Park Service, Montana State University, Colorado State University, Woods Hole Research Center, and NASA will use NASA ESS observations and models to improve the NPS Inventory and Monitoring Programs DSS by hindcasting, nowcasting, and forecasting of park resources to aid management.

I&M using compatible data formats and delivered at intervals synchronized with key management mileposts. The DSS is designed to inform the NPS on the condition of park resources, provide early warning of abnormalities, provide a means for managing the park in the context of the surrounding greater ecosystem, and allow conceptualization of the likely outcomes of alternative future management strategies. This knowledge will facilitate more informed decisions about policy and management such as how to prioritize resources for research.

The numbers and types of observations and predictions developed in this study will vary with the time period (Fig. 2). The full suite of observations and predictions will be generated for the current time period and updated in the future under specified intervals. A subset of key themes will be quantified for the past period 1985 to 2005 and forecast for the future period 2005-2025. This will include climate and land cover and use (considered drivers), and aspects of hydrology, biodiversity, and ecosystem productivity (considered response variables). The purpose of this hindcasting and forecasting is to demonstrate the approach for three response variables that are of wide interest to the NPS. By demonstrating the approach in this study, we will pave the way for NPS to model other response variables in the implementation phase of the I&M Program. We will model each response variable at two or more of the four sites to demonstrate the generality of the models. The family of models used in the study will be

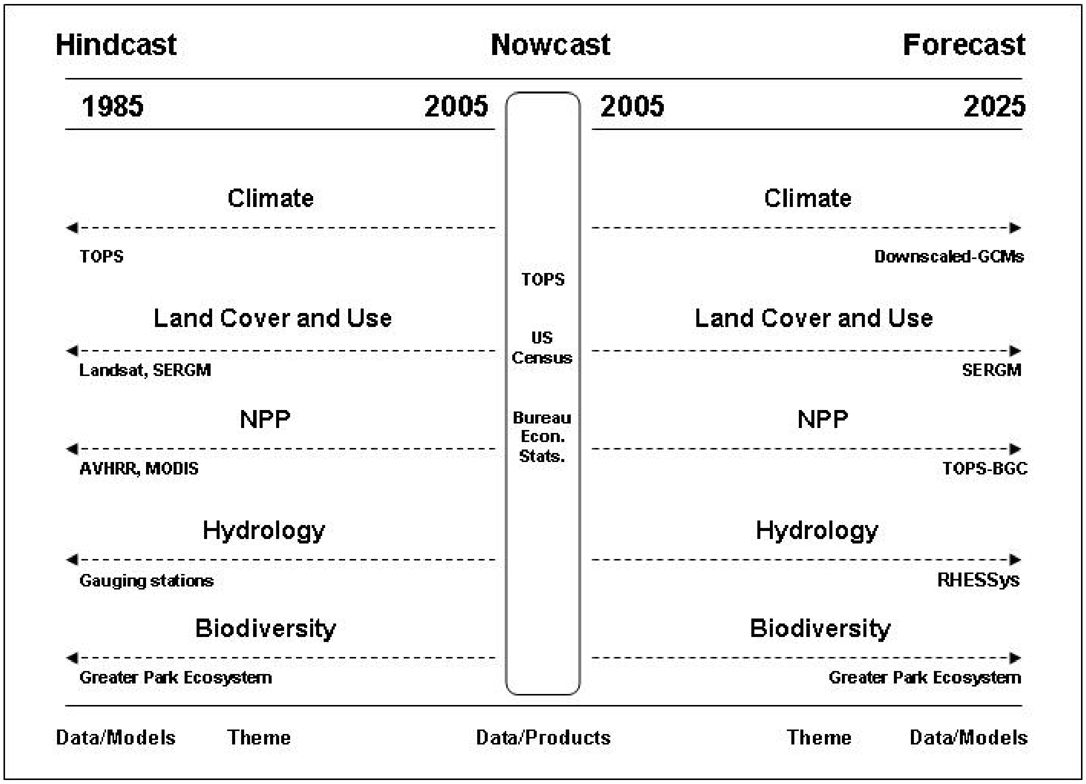

Figure 2. Framework for prediction key themes in the context of the NPS I&M DSS. Shown are the time periods of interest, key themes that will be quantified, and data sets and models that will be used.

linked within the ESRI ModelBuilder software to ensure ready adoption by the NPS I&M scientists.

Pilot NPS I&M Networks

The prototype applications will be implemented in parks from four I&M Networks (Fig. 3) that best leverage past investment by NASA in development of necessary data, models, and infrastructure. These parks are Delaware Water Gap National Recreational Area (Eastern Rivers and Mountains Network), Yellowstone and Grand Teton National Parks (Greater Yellowstone Network), Rocky Mountain National Park (Rocky Mountain Network), and Yosemite National Park (Sierra Nevada Network). These parks represent a diversity of ecological settings, geographical locations, and ecological issues, and they leverage past NASA investments.

Objective 1. Landscape-level indicators and Greater Park Ecosystem Boundaries

A key challenge in supporting the NPS I&M DSS is to select an appropriate set of indicators of change in land cover and use. There are many ways to represent land cover and use; these representations vary in feasibility, accuracy, expense, and relevance to management. Translating maps of land cover and use into measurable, revealing indicators requires knowledge of ecological theory, coupled with expertise in landscape analysis and in NASA ESS data and products. Each of the four pilot networks included in this study have selected indicators. With our NPS I&M colleagues, we will evaluate, review, and if necessary revise the selected land cover and use indicators to increase effectiveness and best take advantage of NASA ESS data and products.

Several criteria have been identified for prioritizing indicator variables for monitoring programs (National Academy of Sciences 2000; Dale and Beyler 2001; Smyth and Franklin 2001). For the NPS I&M DSS, we suggest the selection of land cover and land use indicators that are:

1. related to drivers of change in key ecological responses or index those responses,
2. feasible to monitor (based on data required, cost, and accuracy),
3. anticipatory; able to provide early warning of change in the response variable.

We embrace the NPS I&M method of using conceptual models to prioritize measures of land cover and land use as indicators of landscape changes. Conceptual models in this context are mental representations of cause and effect relationships of how park ecosystems function (Gross 2003). They express hypotheses or knowledge of the factors that drive key natural resource responses and the mechanisms by which the driver influences the response variable. These drivers can then be monitored and used as an indicator of current or possible future change in the response variable.

We have developed a conceptual framework that captures the linkage of national parks to land use change on surrounding lands (Hansen et al. 2005, DeFries et al. 2005, Hansen and DeFries in review). This framework will be used to evaluate I&M indicators

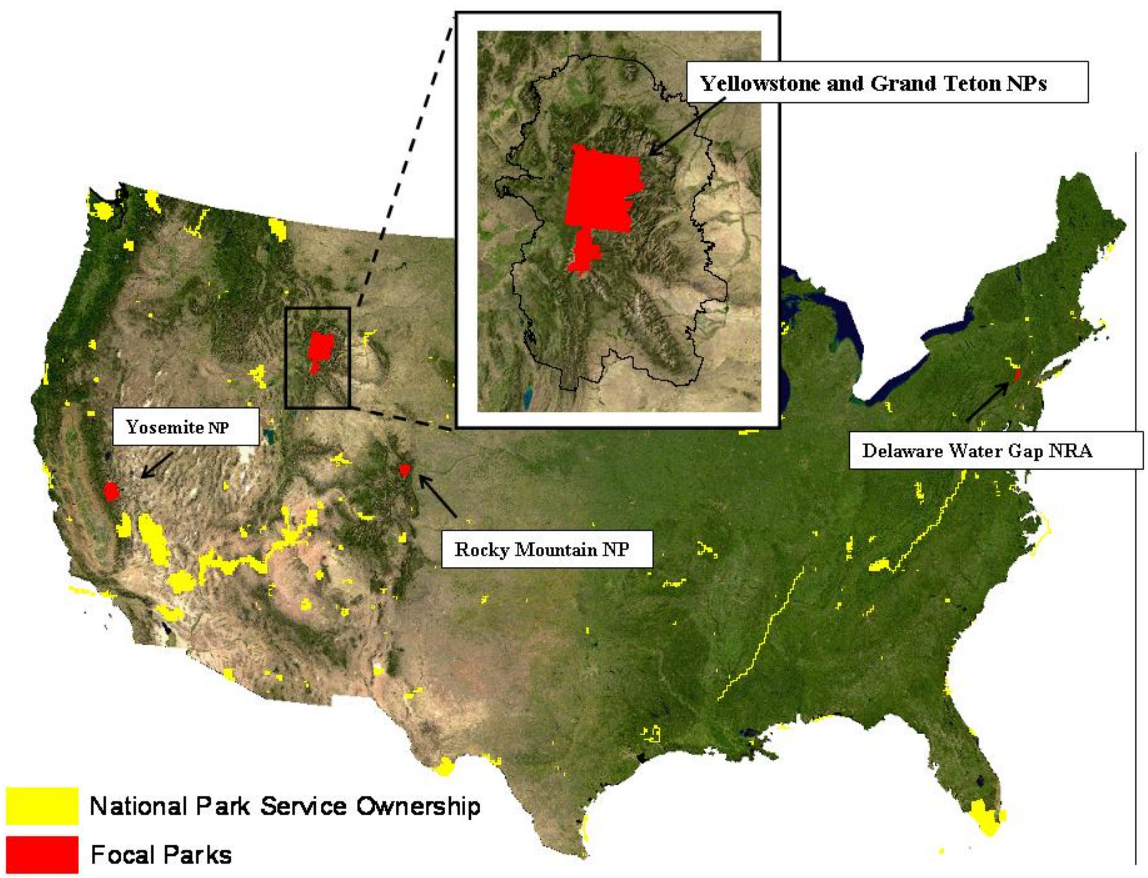

Figure 3. The four focal national parks to be included in this project. The insert for Greater Yellowstone illustrates delineating a greater park ecosystem.

and to select boundaries of the surrounding greater park ecosystem. Boundaries of many National Parks were designated based on factors other than ecological completeness, such as scenic value, thus they tend to lie in portions of the landscape that are relatively harsh in climate and low in soil fertility (Scott et al. 2001). Many ecological processes and organisms may have operated over areas larger than the park. Following reserve establishment, reserves may continue to function as parts of larger ecosystems because surrounding lands continued to provide functional habitats. If land use change reduces habitat quality in the unprotected portion of the ecosystem, ecosystem function and biodiversity may be altered within the park.

The mechanisms in Table 1 provide a conceptual basis for understanding how land use conversion and intensification around reserves may influence the ecology within reserves. These mechanisms have been tested in six greater park ecosystems around the world under NASA NAG5-6005, and form a basis for selecting ecologically meaningful indicators of land cover and use. An example comes from the Greater Yellowstone Network (GRYN) where this conceptual model was used to identify indicators, accuracy and feasibility were assessed, and the extent to which the indicator was anticipatory was evaluated, resulting in a final set of indicators (Jones et al. in review)

Priorities for land cover and land use indicators vary among national parks within the U.S. We will review the indicators previously selected by the Networks within the context of management objectives and with regard to best utilization of NASA ESS data and products. The resulting list of high priority indicators will then be adopted for further development. Feasibility, cost, and accuracy will be assessed by mapping each of the indicators for all or a portion of the network area, and by evaluating methods, cost (in data, personnel, and equipment), and accuracy (based on traditional Kappa statistics and multi-resolution statistics; Costanza 1989; Pontius 2002). Evaluating the relevance to NPS objectives and the extent anticipatory to change will be done by retrospective and forecasting studies.

The ecological mechanisms in Table 1 will be used to define the effective ecosystem around each park. The key criteria for inclusion will be: contiguity of surrounding natural habitat, watershed boundaries, disturbance initiation and run-out zones, and organism

Table 1. Mechanisms linking land use change surrounding parks to biodiversity and ecological processes within parks and criteria for managing regional landscapes to negative impacts. From Hansen and DeFries (In Review).

Mechanism	Type	Design Criteria
Change in effective size of reserve	Species Area Effect Minimum Dynamic Area Trophic Structure	Maximize area of functional habitats
Changes in ecological flows into and out of reserve	Disturbance initiation and runout zones Placement in watershed or airshed	Identify and maintain ecological process zones
Loss of crucial habitat outside of reserve	Ephemeral habitats Dispersal or migration habitats Population source sink habitats	Maintain key migration and source habitats
Increased exposure to human activity at reserve edge	Poaching Displacement Exotics/disease	Manage human proximity and edge effects

movements. These will be mapped with quantitative spatial data and expert opinion. This will be done in workshops with NPS I&M Network scientists. The actual quantification of ecosystem limits will be done by building on recent innovations for the development of functionally defined and weighted analytical boundaries (Poiani et al. 2000; Theobald and Hobbs 2002) that make use of cost-distance weighted methods (Theobald 2005a; Theobald in press).

Objective 2. Integration of Earth-Sun System Products into the NPS I&M DSS

A limitation of the NPS I&M DSS is that it does not currently utilize remote sensing data for continuous monitoring and assessment of park ecosystem conditions, in part due to the extensive processing and computing resources required to utilize daily feeds of satellite data from the Distributed Active Archive Centers. Also, the I&M system does not currently have a capability for long-term forecast and scenario evaluation, especially for detailed analyses of changes in land-cover, hydrology, and biodiversity. The absence of spatially continuous, standardized, park-wide measures of park ecosystems make it difficult for NPS scientists to integrate the disparate I&M data sources to depict baseline conditions. Limited use of ecosystem models also limits the ability of NPS scientists to identify and forecast long-term trends in park-wide ecosystem conditions. Data from NASA satellites and ecosystem models could play a critical role in filling this gap in the I&M DSS, allowing for standardized measures of baseline ecosystem conditions within U.S. national parks and long-term trend analysis.

The NASA TOPS provides an ideal mechanism for integrating NASA ESS data and products into the NPS I&M DSS. TOPS (Nemani et al., 2003) is a modeling framework that integrates and preprocesses EOS data fields so that land surface models can be run in near real-time. Currently, a modified version of the BIOME-BGC model (Thornton et al. 1997) is used to estimate various water (evaporation, transpiration, stream flows, and soil water), carbon (net photosynthesis, plant growth) and nutrient flux (uptake and mineralization) processes. TOPS forecasts variables at a variety of spatial scales, from global net primary productivity (NPP) anomalies at 0.5 x 0.5-degree resolution to local estimates of ecosystem variables at resolutions as fine as 250m. At each spatial resolution, TOPS uses different sources of satellite data (Ikonos to MODIS) and meteorological data (single weather station to global atmospheric model outputs).

We will augment TOPS products with other data sources useful for monitoring land use. These will include data from the US Census Bureau, the Bureau of Economic Statistics, the Farm Bureau, and parcel ownership data (where available). These data sets are readily available, and when combined with the land cover metrics, provide the fundamentals for monitoring landscape pattern metrics, such as connectivity, adjacency, heterogeneity, and habitat patch properties (e.g. Riitters et al. 2002), together with the associated dynamics of land cover and land use change.

As part of the I&M effort, the NPS has initiated a modern information management infrastructure (e.g., staffing, hardware, software) and procedures to ensure that relevant natural resource data collected by NPS staff, cooperators, researchers and others are entered, quality-checked, analyzed, reported, archived, documented, cataloged, and made available to others for management decision-making, research, and education. The NPS is a highly decentralized agency with complex data requirements. The NPS I&M Data Management framework was designed to promote integration and collaboration among parks, programs and agencies and to provide standardized, master databases for those common data sets needed at multiple levels (e.g., park, network, region, national). The framework includes a series of internet-based, master databases to promote integration and enable linkages and data sharing to other external databases (e.g., NPS permitting system, Integrated Taxonomic Information System, USFWS T&E species database, NatureServe, eNature). A second component of the data management framework is a series of desktop applications in MS Access (the NPS standard for desktop relational databases) that can accommodate the same data as the master web-based databases. A third component of the framework is a collection of relational databases that follow the database template scheme, with an integrated link to GIS and associated tools through an Arc-Access Link Tool or geodatabase model.

Efforts conducted under this project to integrate NASA data into the I&M systems outlined above must adhere to the protocols listed in the I&M project plans and specifications (http://science.nature.nps.gov/im/monitor/). In particular, all data proposed for integration under this project will (1) be in a format that is compatible with the GIS systems that are the primary NPS tools for data visualization and analysis, and (2) include extensive metadata compliant with OGC and ESML standards. Meta-data will also be delivered in a format which is compatible with the I&M data template schemes to facilitate automated import into the I&M master databases.

With support from the NASA Research, Education, and Applications Solutions Network (REASoN) program, scientists at NASA Ames are currently working with the NPS to develop systems to integrate TOPS products into the I&M DSS. Under this ongoing effort, TOPS products are being developed in formats compatible with automated import into the I&M DSS. Products are currently delivered in binary and GeoTIFF format via secure servers and automated download and retrieval tools. Tools are also being developed to automate the import of meta-data into the I&M database templates. In addition, under this project NASA is providing expertise and training on the design of data storage and management systems to assist NPS staff in implementing multi-terabyte data archives.

Capabilities for historical analysis or long-term forecasting and scenario evaluation are, however, beyond the scope of the current REASoN-TOPS project. We propose to leverage the REASoN supported effort and extend the capabilities provided by TOPS to incorporate additional modeling capabilities for detailed analysis of long-term changes in land use/cover, climate, hydrology, ecosystem productivity, and biodiversity. These additional modeling tools and products will fulfill a critical need identified within the NPS for a capability to identify potential impacts to park ecosystems resulting from long term changes in climate and land cover. Data from the component models described in the following sections will provide detailed analyses of long term changes in the vegetative and hydrologic patterns within park ecosystems.

Objective 3. Analyses and Forecasts

A key challenge in any monitoring program is to produce results that are useful to decision-makers (Kurtz et al. 2001). A wealth of data can be obtained through monitoring. The challenge is to add value to these data to supply products that are most relevant to management. We will do this by using ecological knowledge and objective quantitative tools to guide the analysis and presentation of monitoring data. First, raw data from satellite or other sources are integrated to appropriate temporal and spatial resolutions (done within TOPS). Spatial patterns are quantified using several landscape metrics. The resulting spatial data and metrics may be used as inputs into simulation models to calculate higher order responses. Data, metrics and simulation results are then analyzed to determine trends over time and space. The results are interpreted and presented in highly understandable outputs.

Land Cover and Use Metrics. To examine landscape change, we will develop a dozen or so landscape metrics that will be computed on a time-series of land cover and land use maps. The specific metrics will be developed through the synthesis of ecological knowledge and vetted with our collaborators (NPS I&M). We will group and evaluate both compositional metrics, such as the proportion of a land cover type in a study area, and structural metrics, such as weighted mean patch size. Our evaluation criteria will address recent criticism of landscape metrics (Li and Wu 2004). First, by grounding our metrics within an ecological framework (see Objective 1). We will extend typical structural metrics about patch shape, size, and arrangement to allow incorporation of behavior and scaling of processes (i.e. functional connectivity; Baudry and Merriam 1988; Theobald 2005b). Second, we will use landscape indices that are robust to data artifacts and assumptions of normal distributions (e.g., average patch size). All metrics must have well-defined theoretical bounds, monotonic relationships, and be sensitive to the proportion of land cover (Neel et al. 2004). Third, we will explore the use of Monte Carlo methods (e.g., bootstrapping, permutation) to test differences between estimated (observed) patterns and possible null models and/or realized patterns holding specific elements of pattern constant. Comparing a metric computed for an observed pattern against a generated distribution will provide a clearer understanding of significant differences in landscape metric values (Remmel and Csillag 2003).

We will pre-process and provide common data sets (e.g., land cover) that will enable consistent analyses to be conducted at both broad and small extents (Network to park unit). Because nominal (class) data, such as land cover types do not scale readily, we will develop methods to represent data as continuous variables (one layer for each cover class), and also incorporate continuous representations of land cover (% impervious, % tree cover) so that systematic bias does not occur. In addition to providing data sets, we will refine techniques for computing spatial statistics, such as spatial autocorrelation (e.g., Moran's *I*), through ArcGIS tools that the NPS I&M networks use (Theobald 2005b).

Trend Analysis and Forecasts. Our framework will allow two types of trend analysis. First, indicators will be computed for each time step, and then the results will be summarized using time-series analysis and graphs. Second, we will compute indicators based on the spatial differences between time steps, allowing changes at specific locations to be quantified. Graphics tools will be integrated to facilitate interpretation by users. These historic analyses will be done for climate, land cover and use, hydrology, ecosystem productivity, and biodiversity. These same variables will be forecast to 2025 using simulation models as specified in Fig. 2.

Climate. Data on past climate will be generated from point-source data using the Surface Observations Gridding System (SOGS). SOGS automatically retrieves, stores, and interpolates surface meteorological observations for almost any region of interest. The system uses a variety of interpolation techniques, is adaptable for use with multiple data sources, and interpolates to different grid resolutions (Jolly et al., 2005). The gridded fields produced by SOGS are maximum and minimum temperature, VPD, precipitation, and solar radiation. We will use SOGS to produce 1-km resolution daily meteorological surfaces from historical data for each pilot area for 1985-2005. The results will be used to establish baseline meteorological conditions for the parks to facilitate identification of trends and anomalies. In addition, long-lead climate forecasts will be obtained from the NWS Climate Prediction Center and used to drive ecosystems models to produce forecasts of ecosystem conditions to 2025. We will use TOPS to generate VEMAP (Kittel et al., 1995) style ensemble predictions using a number of GCM-derived climate predictions. SOGS will be used to downscale GCM output to scales that are appropriate for analysis of ecosystem impacts within the parks.

<u>Land Cover and Use</u>. Our historical analysis of land cover and use will take advantage of the maps that have been developed in the past for each of the pilot sites. Because exurban and urban development is difficult to detect from satellite imagery, we will use other methods to spatially distribute human density across these landscapes. The Spatially Explicit Regional Growth Model (SERGoM) (Theobald 2005) distributes housing densities -- a stronger variable of landscape effect than population density -- across the landscape based on ownership, land cover, and infrastructure. We will use the model and block-level US Census data to quantify rural and urban land uses at a 100-m grain across the study areas for 1985 and 2005. Trajectories of change will be quantified using the methods of Parameter et al. (2003).

Our experience in forecasting land use change (e.g., Jantz et al. 2003; Jantz et al. 2005b; Theobald 2005b) will be applied to simulating likely changes to 2025 for the study areas. The baseline future scenario will be that already produced by SERGoM (Theobald 2005). Other scenarios will be generated by adjusting model parameters such as population growth rates (e.g., county forecasts), allocation of new growth to include NASA-derived land cover data, potential protection measures (e.g., land protection programs), and other policy options. The main focus is the production of future development maps and growth patterns under various policies in order to explore their potential impact on lands within the selected park ecosystems, including those nearby parks. The various scenarios will be developed in close collaboration with NPS staff (e.g, after Jantz et al. 2003, Theobald et al. 2000; Theobald and Hobbs 2002) to ensure relevance to specific park management and monitoring objectives. This will include manipulating suitability layers in the land use change scenarios to develop appropriate and relevant land use and land protection alternatives (e.g., Gude et al. in review).

<u>Hydrology</u>. The links between land cover and water quality have long been known, but not until recently have analyses of the interplay between biological and hydrological processes over large areas at fine spatial resolution become feasible. The primary aim of this component of the proposed work will be to advance the use of land cover and land use on the discharge behavior of waterways within the selected NPS ecosystems,

establish how this varies with the rates and patterns of urbanization, and how waterways are affected under different management schemes.

We will exercise the Regional Hydro-Ecological Simulation System (RHESSys) model, a well-established distributed hydrologic model (Band et al. 1991; Brun and Band 2000), using the suite of data sets and derivative products from TOPS, as well as landscape variables such as land cover configuration and riparian buffer metrics. Using TOPS, we have the ability to automatically generate and adjust the output files that direct the flow of execution of RHESSyS. Inputs to RHESSyS from TOPS include LAI and land cover, as well as spatially continuous meteorological surfaces from SOGS (max/min temperature, precipitation, VPD, and solar radiation). We will also incorporate landscape configuration metrics as gridded layers in the distributed model, including mean distance from impervious areas to the stream channel along a topographically defined flow path, and other metrics that define the dispersion or aggregation of land cover within the landscape (e.g., King et al. 2005, Snyder et al. 2005). After TOPS' execution completes, databases are populated with the outputs for use in RHESSyS, which ingests these and other data sets to produce modeled estimates of a range of variables including snow cover, soil moisture, evapotranspiration and runoff as gridded outputs (maps). Initiation of additional iterative modeling runs is done to calibrate runoff to gauge data, of which we have compilations for the selected park ecosystems. The influence of simulated management approaches will be evaluated via the devised scenarios.

We will also make use of our land cover products and model simulations to predict and map the biotic health ranking of streams within small watersheds under present conditions (i.e., year 2000), and then into the future under our various modeled land use change scenarios.

<u>Ecosystem Productivity</u>. Net Primary Productivity (NPP) provides a useful measure of plant growth and can be an important indicator of overall ecosystem health. Decreases in NPP may be indicative of disturbance events (e.g., fire, blowdown), vegetation stress due to changes in hydrology, changes in snow melt patterns, and changes in climate. Increases in NPP may indicate a response of vegetation to early seasonal warming or increased levels of nitrogen and other nutrient inputs to ecosystems from atmospheric and aquatic pollution. At NASA Ames Research Center we currently use TOPS to produce maps of NPP anomalies from global to local scales. Satellite inputs used in the production of NPP include LAI/FPAR, NDVI, and Landcover data from Landsat ETM/TM, AVHRR, and MODIS. Using TOPS' extensive historical data record from these instruments for 1982 to the present, we will be able to calculate the baseline NPP for park ecosystems included in this study, provide maps of current NPP for park ecosystems, and monitor for anomalies in ecosystem NPP. NPP anomaly maps will provide a useful indicator to NPS staff of impacted ecosystem function and will alert NPS scientists to regions within a park that require additional monitoring and investigation.

In addition to the establishment of baselines and continuous monitoring, we will use climate forecasts and maps of predicted land cover described previously to produce forecasts of future ecosystem NPP conditions.

<u>Biodiversity/habitat</u>. Biodiversity encompasses a large variety of components and a number of approaches have been developed for comprehensive assessment. Biodiversity

within protected areas such as national parks is likely most at risk from near-term changes in the surrounding landscape due to human land use. Thus, we will use the conceptual framework of Hansen and DeFries (in review) (Table 1) to guide our biodiversity assessments in our pilot NPS I&M Networks. Thus, we will work with NPS collaborators from each of the networks to assess which of the mechanisms above are of concern and design the biodiversity analyses for the network accordingly.

We have previously applied this framework to draw implications for regional-scale management for four greater park ecosystems around the world (DeFries et al. in review). For example, NPS personnel in the Greater Yellowstone Network were concerned about the effects of rural home development and agriculture on seasonal and migratory habitats of wildlife in the national parks. Gude et al. (in review) obtained data on rural home and agriculture from 1860 to present and overlaid these data for decadal intervals on eleven indices of biodiversity. They found that the area of these biodiversity indices had been reduced by up to 24% across the Greater Ecosystem. They created maps of the undeveloped private lands that were most important for biodiversity and recommended that conservation strategies be aimed at these locations.

Forecasting of biodiversity will be done using the same methods as described above for hindcasting. The key biodiversity indices identified by the NPS collaborative analysis will be projected to 2025 under various climate and land use and management scenarios. The predictions of the various scenarios will be compared to evaluate the likely effectiveness of the alternative management strategies.

Objective 4. Integration into NPS I&M's DSS Framework.

"The right information, to the right people, at the right time, in the right format"

Tools described above will produce information that flows directly into NPS reporting and decision making processes. Each I&M Network Monitoring Plan must document a comprehensive strategy for regularly reporting monitoring data in formats appropriate for various user groups (http://science.nature.nps.gov/im/monitor/docs/monplan.doc). In addition, a component of the I&M DSS is an existing, highly structured information system. We will enhance the I&M infrastructure by feeding data and information into existing communication plans and processes, and use our knowledge of the NPS planning process to develop outputs compatible with I&M data management standards and NPS planning needs. In short, our primary goal is to deliver the right information, to the right people, at the right time, in the right format.

The NPS planning at the park level includes production of a park General Management Plan, Resource Stewardship Plans, a 5-year Strategic Plan, and implementation plans to achieve specific goals. Each park must incorporate Department of Interior strategic goals in their planning process, and these DOI goals provide clear guidance on the types of information that parks will have to report. Most parks are concerned about their ability to report to these new goals. The DOI Strategic Plan (http://www.doi.gov/gpra/) defines three major goals that our system could report to: 1) Improve health of watersheds, landscapes and marine resources; 2) Sustain biological communities; and, 3) Protect cultural and heritage resources. To meet reporting requirements, NPS will integrate information from all available sources, and we have a timely opportunity to make NASA products an operational component of the NPS strategy to meet national reporting requirements. Integration into the planning and reporting process represents a second level of integration.

Parks address a wide variety of unstructured needs for natural resource information, including responses to disturbances (e.g., floods, hurricanes, fires), development plans (e.g., roads, houses), and land use changes (e.g., dams, logging, mining). Our tools are designed to be flexible to provide information relevant to most broad-scale management issues. Historical and current land use maps, forecasting tools, and quantitative data relating land attributes to park resources provide critical information for responding to routine park management needs.

The NPS I&M Program charge is to be the primary source of scientific information for supporting decisions on management of park natural resources. The I&M DSS will provide information via annual reports, long and short term planning documents, and by conducting routine evaluations at the park level. Our system is designed to support all of these activities.

To enhance the transfer of our approach to the NPS I&M, we will package the metrics and models in the form of a set of GIS-based tools using ESRI's ModelBuilder framework. ModelBuilder is a visual-based programming framework that has emerged as a primary way to extend ESRI's ArcGIS product (the primary software used by NPS I&M). We found strong support from I&M staff during a technical workshop in May 2005 regarding the delivery of a set of spatial sampling tools in ModelBuilder.

Innovative Aspects

The study is innovative in several ways that will enhance the NPS I&M DSS and facilitate improved decision making. The research team is a unique combination of highly talented and productive scientists with the balanced combination of skills to greatly improve the NPS I&M DSS. This expertise includes delivery of NASA data and products as produced by the TOPS Program, land cover and use mapping and analysis, forecasting of ecosystem processes and biodiversity, development of the NPS I&M DSS, and close working relationships with the NPS I&M staff. The project will provide mainstream delivery of highly refined TOPS data sets and metadata to the NPS. The study employs a strong conceptual framework linking land use around national parks to biodiversity and ecosystem function within parks. Sophisticated methods of hindcasting, nowcasting, and forecasting are used in the study. The data and tools used in the study will be packaged within a software system that is readily usable by NPS personnel. The study leverages resources from three other large NASA projects or studies (TOPS, a REASoN study, and two LCLUC studies) and the NPS I&M Program (see NPS cost share). Finally, the close collaboration with the NPS I&M networks ensures that the results will be implemented within the NPS.

Systems Engineering Approach

Confidence in each data layer produced by the project will be validated and utility of data layers will be evaluated. Above, we describe methods of quantifying the accuracy and utility of landscape metrics. Simulation results for forecasts will be calibrated and validated by quantifying the extent to which hindcasts match historic data. The geographic generality of the simulations will be quantified by cross-validating within and between watersheds. For example, applying threshold criteria provides maps of watershed stream health rankings that can be tested against independently defined rankings based on the in-stream measurements collected locally. This use of the results to inform management goals via scenarios analysis, as implemented via the NPS DSS, will aid strategies to reduce the impacts of developed areas on park resources.

Management Approach

We plan to execute the study as a tightly integrated team. While each scientist will have a lead responsibility (see pg 2), all of us will participate in decisions about overall study direction and integration. This will be done through frequent conference calls and through twice annual workshops. Integration will be further advanced by each modeling effort being done at two or more case study networks and by graduate students funded through the project spending a semester at a second of the four institutions involved with the study. We each currently have strong working relationships with NPS I&M Network scientists. In this project these I&M scientists will be essential members of our study team and involved in all phases of the work. The cost share commitments of the NPS scientists is evidence of their dedication to the project. Workshops with I&M scientists throughout the study will ensure that the software and results best meet the needs of the NPS and will be integrated into the ongoing NPS DSS.

Issues and Risks

All collaborative, multidisciplinary and complex research projects contain risks associated with the chain of data processing and analysis steps leading from one participant to the next. This is particularly true in applied research in which the "end user," in this case the Park Service, has a suite of well defined management and monitoring priorities to support their decision making. Whereas the NPS has a long term commitment to the I&M program, we recognize that these may change through time due to annual budget priorities, changes in leadership, or other factors. We also recognize that the I&M program has a great deal of information through which they must sort and prioritize relative to their objectives. We have designed our project from the outset with the full participation of the I&M program lead (Gross) in order to tailor the work to the specific needs of the program. We have also leveraged a wide range of ongoing activities of each of the participants, drawing on their areas of expertise, with these specific objectives in mind. As such, risks associated with changing priorities are built in to the proposed work in that we can modify and re-weigh our emphasis areas and relative contributions as needed.

Transition Approach/Activities

Our primary approach for transitioning our project to NPS is to enforce, from the very beginning, a high degree of consistency between identified NPS needs and products from the project. First, results for the image analyses and model outputs are closely aligned to previously identified, high-priority vital signs**.** Every I&M Network with a list of priority vital signs has identified landscape dynamics as a high priority – currently a total of 17 networks that plan to monitor landscape dynamics in 184 parks (Table 2). We will use the ESRI programming platform (see Objective 4) because NPS has an agency-wide license for ESRI products and a staff with a high degree of expertise using and programming in the ESRI environment. We have required each participating I&M

Network to provide cost-sharing and collaborate in the program design, and we have designed a communication plan that includes regular informative updates by Dr Gross to the entire I&M Program and Advisory Council, and training of selected NPS staff as program experts.

The I&M Program employs more than 60 full-time data managers and ecologists. From this pool of highly qualified candidates, we will recruit a relatively small number (about 5) of the most interested, motivated, and qualified candidates and provide them with additional training in the use and application of our tools. These individuals will serve as 'expert consultants' and ambassadors within the I&M Program. The I&M Program has an established tradition of sharing expertise and experiences among Networks, and this strategy leverages the existing culture. We think a broad-based communication plan, combined with a highly focused training program, will best ensure that everyone in the I&M Program knows what our project can deliver, and that there is adequate capacity to rapidly expand the use of our products to Networks throughout the I&M Program.

Performance Measures and Project Management Metrics

We will evaluate the efficacy of the project by documenting use of NASA imagery and products by the I&M Networks at the beginning and end of the project.

Table 2. High-priority vital signs or measures identified by the first 17 I&M Networks that are supported by remotely sensed data or model results. An asterisk (*) indicates vital signs identified by networks that are prototypes for this project.

Category	Example vital sign or measurement
Extreme disturbance events	Blowdowns, floods, etc
	Vegetation disturbance patterns
Fire and fuel dynamics	Fire effects on vegetation communities*
	Fire occurrence and extent*
	Fuel dynamics and condition
Landscape dynamics	Anthropogenic modifications (e.g., shoreline manipulation)
	Habitat fragmentation
	Land cover*
	Land use*
	Land use in and near parks*
	Landscape composition and dynamics*
	Landscape pattern*
Nutrient dynamics	Biogeochemical cycling*
	Nutrient dynamics*
Productivity	Land condition - productivity
	Net primary productivity*
	Plant phenology
	Primary production*

Seventeen (of 32) networks have identified priority vital signs and all 17 monitoring networks plan to monitor ecological attributes that are routinely measured, using existing techniques, via remotely sensed data (Table 2). An informal survey of all I&M Networks revealed five networks with a draft protocol (Oakley et al. 2003) or a current contract to develop the use NASA imagery for ecosystem monitoring. No Network has yet obtained an approved protocol that relies on NASA imagery. I&M Networks have identified the use of RS data as a high priority, but they have not yet found a way to operationalize the use RS data. In the NPS, only the Fire Program routinely uses NASA products to regularly monitor condition of natural resources. We expect this project to catalyze a rapid increase in the use of NASA products by I&M Networks, and our benchmark process will document this result. Products from this project could flow into a wide range of park decision-making processes, and we propose an adaptive process to benchmark the success of the project. At the beginning and end of the project, we will survey all I&M Networks and quantify:

1. The number of I&M Networks with approved or draft protocols relying on NASA products.
2. The number of parks that are using or have plans to use products provided by this project.
3. The number of I&M Networks routinely reporting results from this project, or with concrete plans to use project results.
4. The number of Park planning documents or planning processes that used or incorporated results from this project. NPS planning includes watershed condition assessments, General Management Plans, Resource Stewardship Plans, restoration plans, etc.
5. Other opportunistic uses of project products. These could include such things as species management plans, invasive species management, and local land use planning.

Anticipated Results/Improvements

We will achieve four results that add value to the NPS I&M DSS. First, we will provide technical and analytical tools for displaying and interpreting monitoring data to make them most valuable to managers, interpretative staff, citizens, and politicians. We will develop rigorous models that link observations of changes in land cover and land use with ecological processes and management decision points. In addition, we will work with park managers and I&M staff to evaluate NASA and other data sets on land cover and use that can best drive the NPS I&M DSS. We will demonstrate these in the field to park managers and will develop the software needed to implement the analytical tools by park and I&M staff.

The proposed work will inform the NPS I&M decision making process in a consistent and rigorous manner. Use of these NASA ESE products will allow the NPS to build substantially upon their current I&M Program by exercising alternative future management scenarios, including those focused specifically on different land use and management treatments. In this way, the NPS will be able to regularly adapt their management process, incorporating current trends in indicators while exploring the impacts of various possible alternative scenarios - all in a spatial context.

Schedule and Workplan

Performance measures for this project include the development and/or enhancement of products and the degree at which our work penetrates the day-to-day activities and decisions of the NPS. The success of this project relies on close collaboration and joint ownership in project results. Here we include measures that explicitly address development of this partnership.

Year 1 Milestones

- Establish the collaborative development process and identify development team members from each NPS focal Network.
- Complete survey of NPS I&M network scientists needed to support evaluation and performance measures.
- Identify and articulate sets of indicators that can be used to monitor high priority vital signs identified by Networks. These sets will include core indicators that apply to most parks, and 'subsets' specific to topologies of parks. In collaboration with Networks, agree on descriptions of each indictor, articulate specific monitoring goals and objectives, and identify appropriate measures. These descriptions, goals, and objectives will be incorporated into approved, long-term monitoring protocols.
- Quantify the boundaries of greater park ecosystems for the four pilot networks.
- Develop functional prototype software to ingest common data formats (i.e., data acquisition) and standardize pre-processing of most common digital data sources.
- Compile and pre-process (where necessary) data required for land cover and use mapping and analyses of past to present changes for each study area.
- Develop and apply functional prototype land use models and initiate calibration and testing in two pilot Networks.

Year 2 Milestones

- Present prototype products to Networks and modify as needed.
    - Conduct a second series of collaborative design workshops.
    - Obtain a written review and confirmation from collaborative design partners that software and information outputs closely match Network needs.
    - Obtain a written review from park management staff that information outputs match decision support needs.
- In collaboration with Networks, develop written standard operating procedures consistent with Oakley et al. (2003) that can be adopted by Networks as part of an approved monitoring protocol.
- Produce a 'landscape monitoring report' for pilot Networks and obtain written evaluation.
- Achieve integration of software modules to ingest and analyze data, project land use changes, and display results.
- Map land cover and use changes from past to present and analyze trends to provide validation and verification of indicators.
- Develop alternative future management scenarios to be used in forecasting.

Year 3 Milestones

- By mid-year, demonstrate fully functional software for ingesting and processing image data products and digital GIS data sets (e.g., census, EPA, data sources).
- Complete documentation of all software, analytical procedures, outputs, and documentation on interpretation of results and analyses.
- Model and evaluate alternative future management scenarios to identify critical thresholds in land change and to evaluate management approaches.
- Capacity transfer: Complete training of Network and park staff on use, maintenance, and embellishment of DSS tools.

Summary of Proposal Personnel and Work Efforts

Name	Role	Lead Responsibilities	Commitment (% of year)
Andrew Hansen	P.I.	Overall coordination Indicators and ecosystem boundaries Habitat modeling	.17
Scott Goetz	Co-P.I.	Land cover and use analysis Hydrology modeling	.10
John Gross	Co-P.I.	Coordination with NPS I&M Benchmarking and performance standards Integration of results into management	.20[1]
David Theobald	Co-P.I.	Land cover and use modeling Land cover and use analysis GIS tools with ModelBuilder	.08
Forrest Melton	Co-P.I.	Data interface with TOPS Climate modeling NPP and hydrology modeling	.10
Rama Nemani	Co-P.I.	Data interface with TOPS Climate modeling NPP and hydrology modeling	.10
Robert Bennets	NPS Collaborator	Integration with Greater Yellowstone Network	.05[1]
Robert Daley	NPS Collaborator	Integration with Greater Yellowstone Network	.05[1]
Billy Schweiger	NPS Collaborator	Integration with Rocky Mountain Network	.05[1]
Brent Frakes	NPS Collaborator	Integration with Rocky Mountain Network	.05[1]
Matthew Marshall	NPS Collaborator	Integration with Eastern Rivers and Mtns Network	.05[1]
Nathan Piekielek	NPS Collaborator	Integration with Eastern Rivers and Mtns Network	.05[1]
Andi Heard	NPS Collaborator	Integration with Sierra Network	.05[1]

[1]Salary provided by NPS I&M Program

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